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Evaluation of the X-43A Scramjet Engine Controller Performance by Monte Carlo Technique

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Space Administration

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ABSTRACT

A Monte Carlo analysis has been conducted to evaluate the performance of the scramjet engine controller for the X-43A. The Propulsion System Controller (PSC) logic was evaluated to assess the effectiveness of a proposed unstart protection algorithm with regard to preventing engine unstarts and achieving vehicle performance goals. The Monte Carlo data obtained from a high fidelity simulation predicts that utilizing the unstart protection logic significantly reduces the risk of unstart by keeping the isolator margin at or above its desired value. The results also show that the unstart protection algorithm does not significantly reduce the probability of meeting the project's primary acceleration goal, thus justifying its suitability for use within the X-43A PSC.

NOMENCLATURE

6-DOF	six degree-of-freedom
8-ft HTT	8-Foot High Temperature Tunnel
AHSTF	Arc Heated Scramjet Test Facility
DFRC	Dryden Flight Research Center
GN_2	gaseous nitrogen
GH_2	gaseous hydrogen
HXEM	Hyper-X Engine Model
HXLV	Hyper-X Launch Vehicle
HXRV	Hyper-X Research Vehicle
IMG	isolator margin goal
LaRC	Langley Research Center
MC1	execution of MCAT with unstart protection algorithms disabled
MC2	execution of MCAT with unstart protection algorithms enabled
MCAT	X-43A HXRV Monte Carlo Analysis Tool
NASA	National Aeronautics and Space Administration
PSC	Propulsion System Controller
psf	pounds per square foot
SiH_4	silane
SIM	X-43A HXRV Batch Simulation
UAG	unclassified acceleration goal
X-43A stack	HXRV, adapter, and HXLV configured together for launch
σ	standard deviation

INTRODUCTION

The overall goal of the Hyper-X program is to demonstrate and validate the technology, experimental techniques, and computational methods and tools for the design and performance predictions of a hypersonic aircraft with an airframe-integrated dual-mode scramjet propulsion system.[1] The first order success criterion is the acceleration of the Hyper-X Research Vehicle (HXRV) using a scramjet propulsion system at Mach numbers 7 and 10. An obstacle to meeting this performance goal is the potential for an engine unstart.

A high performing Propulsion System Controller (PSC), or computer controller of the scramjet engine, is a necessary element of successfully achieving the Hyper-X goal. The need to provide high engine performance while preventing an engine unstart demands a scramjet engine controller. An unstart is a violent unsteady phenomenon which occurs only with internal supersonic flow and when there is no physical solution to connect the inlet to the exit. An unstart results in high stress transient loads on the engine, reduced air mass capture, rapid thrust loss, and high drag. An unstart typically leads to an engine flameout condition. Due to its small scale, the X-43A does not carry enough onboard fuel and ignitor for re-light capability in the event of an unstart. Thus, as derived from the first order success criterion, engine unstarts are undesirable for the X-43A.

Avoiding engine unstarts is highly desirable for the X-43A. For the Mach 7 vehicle, unstarts are more likely to occur at higher fuel flow levels; this is also where a higher probability of positive acceleration is expected. The PSC must be designed so as to achieve and maintain a balance between acceleration (performance) and unstart (operability). A trade-off must be made between programmatic goals and risks of an unstart.

The NASA (National Aeronautics and Space Administration) Dryden Flight Research Center, Edwards, California, (DFRC), conducted a statistical analysis utilizing a methodology known as the Monte Carlo technique to evaluate whether the PSC can achieve the performance objective without causing an HXRV engine unstart. A high fidelity vehicle simulation was used to evaluate the effect of parameter uncertainties on the ability of the PSC to achieve the desired engine performance and unstart protection. Unstart protection logic was evaluated in the PSC to assess its potential for improved engine operability (reduced unstarts) and its effect on performance predictions. The results are presented in this paper and limited to available unclassified information and data.

This paper summarizes the Monte Carlo analysis conducted on the PSC utilizing the X-43A HXRV Batch Simulation (SIM). The process used to complete the analysis is presented, with limitations and assumptions. A discussion of the results includes an evaluation of the trade-off made between meeting the project performance goals and reducing the risk of an engine unstart. Finally, a summary of the statistical results is presented that includes the predicted probability of successfully meeting established performance goals.

VEHICLE DESCRIPTION, COMPONENTS, AND MISSION

The flight test vehicle is described below. Subsystems related to this report, such as the fuel system and the PSC, are emphasized. A general description of the research mission is also presented.

Flight Test Vehicle

The X-43A flight test vehicle has been designed to meet the above-mentioned objectives and to achieve the program goal by meeting the success criterion of positive acceleration.[2] Figure 1 shows the X-43A, which is comprised of the Hyper-X Launch Vehicle (HXLV), the Hyper-X adapter, and the HXRV. The HXLV, a modified Pegasus® first-stage solid rocket booster (procured from Orbital Sciences Corporation, Chandler, Arizona), will deliver the HXRV to its test condition. The Hyper-X adapter connects the HXRV to the HXLV and also contains additional commodities that supply gaseous nitrogen (GN_2) purge and water/glycol coolant during boost. As can be seen in figure 2, the HXRV carries its own fuel, flight controls, telemetry, coolant, and purge systems for free flight at the desired test condition. When the three components are connected together, they comprise the X-43A stack.

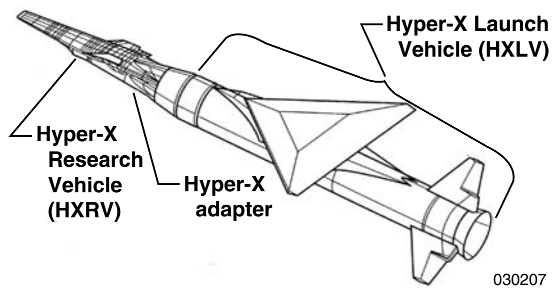


Figure 1. Wireframe diagram of X-43A stack.

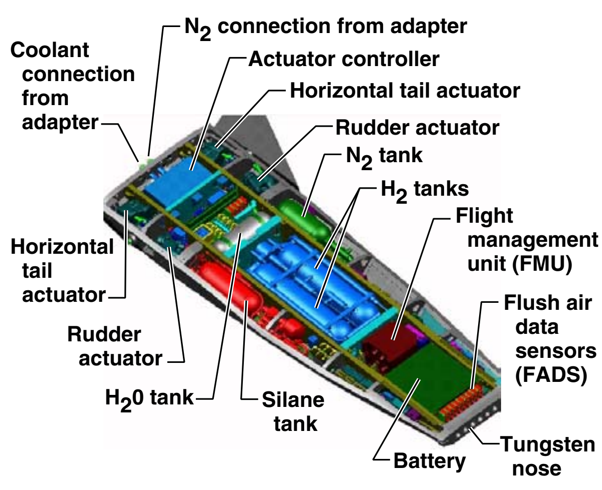


Figure 2. HXRV internal components.

Fuel System

The scramjet engine uses gaseous hydrogen (GH_2) fuel with a gaseous silane (SiH_4)/hydrogen(H_2) mixture used for ignition. The SiH_4/H_2 mixture and the GH_2 are stored in separate tanks onboard the HXRV (fig. 2). The fuel delivery system is designed in a blowdown arrangement with the flow rates of each gas controlled through a main control valve. Mizukami gives details of the fuel system layout.[3] Due to vehicle size, the abundance of instrumentation, and the blowdown design of the fuel system there is limited space for fuel storage. This limits the engine experiment run time to roughly 11 sec. Figure 3 is a sketch of the nominal fueling profile for the Mach 7 flight. The ignitor flow is initiated shortly before the GH_2 flow is initiated, thus providing a stable flame-holder during ignition of the GH_2. Next, the GH_2 flow rate is increased as the ignitor is decreased. Following a stable fueling of GH_2 only, the GH_2 fuel flow is increased to its maximum scheduled value. Following a period of stable fueling, the fuel flow is slowly decreased before shutdown. The fueling profile for the Mach 7 flight was developed through testing at the NASA Langley Research Center (LaRC) in the 8-Foot High Temperature Tunnel (8-ft HTT).[4, 5]

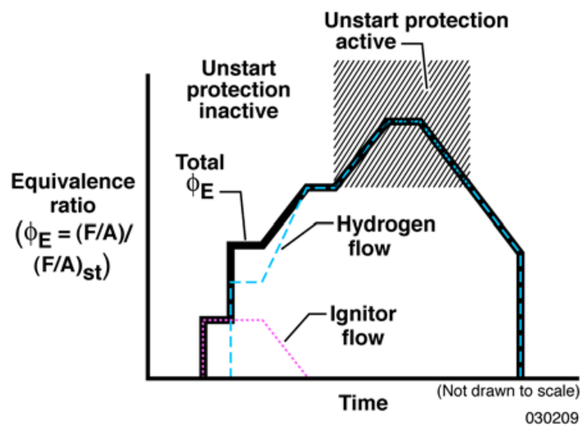


Figure 3. X-43A Mach 7 commanded fuel profile.

Propulsion System Controller (PSC)

The PSC monitors and controls all key propulsion subsystems including the fuel (GH_2 and ignitor), coolant, and purge systems. It provides closed-loop control of the mass flow rate of both the GH_2 and the ignitor to the engine and commands the cowl door actuator. The PSC was designed to reduce the risk of unstart while maintaining a high probability of achieving the acceleration goal.[6] The PSC provides control of the GH_2, ignitor, and cowl subsystems for the duration of the engine experiment. The PSC independently controls the flow rates of both the GH_2 and the ignitor subsystems through the use of motorized control valves. The fuel flow of both the GH_2 and the ignitor are controlled utilizing proportional-integral-feed-forward controllers. The cowl position is electronically controlled to fully open or closed through the use of an electromagnetic actuator.

The PSC logic does not allow for a restart if an unstart or engine flameout occurs (primarily because of limitations in the onboard consumables). Therefore, the PSC was designed to provide robust engine ignition and operation over a range of possible flight conditions, and to provide unstart monitoring and prevention logic. It also provides limited error detection and accommodation.

The PSC reduces the risk of unstart through unstart prevention algorithms. These algorithms monitor engine isolator pressures in real time for potential unstart conditions. If potential unstart conditions are detected, the PSC reacts by reducing the fuel flow, which reduces vehicle performance. The unstart prevention algorithms were developed specifically for the PSC by Boeing Phantom Works, Huntington Beach, California. The early versions of these algorithms were originally developed during the Scramjet Controls Research (SCR) wind tunnel tests. The SCR tests were performed on the Hyper-X Engine Model (HXEM) in the Arc Heated Scramjet Test Facility (AHSTF) at LaRC. Because of distribution restriction issues, the details of the unstart protection algorithms are not presented here.

The PSC software has been extensively ground tested. Boeing completed software tests including unit test, unit integration test and Hardware-In-the-Loop (HIL) verification test. LaRC wind tunnel tests supported software development and verified engine performance. PSC-related ground tests at DFRC included additional HIL (software validation and sensor failure accommodation), and Vehicle-In-the-Loop (VIL) (integrated system validation) tests.

Research Mission

There are three planned expendable flights of three X-43A vehicles. The first two flight tests are designed to be flown to Mach 7; the third flight test is designed to be flown at Mach 10. The desired test condition for the HXRV is 1000 psf of dynamic pressure at both Mach 7 and an altitude of approximately 95,000 feet, and Mach 10 and an altitude of approximately 110,000 feet. The X-43A stack is air-launched from a B-52 west of Los Angeles, California, over the Naval Air Warfare Center Weapons Division Sea Range. Figure 4 shows a sketch of the nominal flight profile. Each of the X-43A vehicles is expendable, and the flight profile ends with the HXRV splashing down into the Pacific Ocean. There are no plans to recover any of the vehicles.

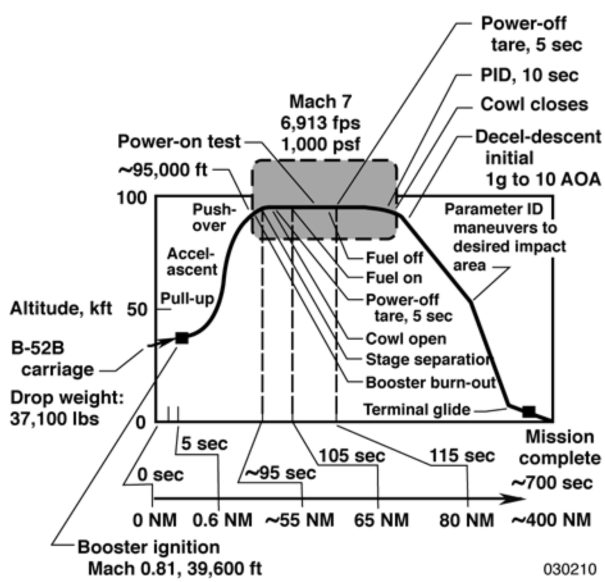


Figure 4. Nominal X-43A Mach 7 flight trajectory.

The first flight of the X-43A occurred on June 2, 2001. However, shortly after release from the B-52, this X-43A stack lost control and was terminated before reaching its desired test condition.[7] The remaining two X-43A vehicles are scheduled to be flown at Mach 7 and 10, respectively.

TEST TECHNIQUE AND TOOLS

A description of the test technique and test tools used in this analysis is given below. Details of the Monte Carlo test technique, the simulation used during this analysis, and the Monte Carlo tool that was developed to facilitate the analysis are presented.

Monte Carlo Technique

Monte Carlo analysis is a commonly used technique to assess a system's performance to predicted parameter variations by means of a stochastic process. It consists of independently varying all model inputs within the known or estimated uncertainty bounds. Random combinations of input uncertainties will often produce different, and potentially worse, results than deterministically varying a single uncertainty or set of uncertainties. This type of analysis consists of making multiple simulation runs, with each run containing a unique set of parameter variations. Also, the output distributions of non-linear systems will not necessarily be Gaussian. The output distributions will simply reflect the response characteristics of the system. A close examination of these response characteristics and the associated probability functions will yield insight into the systems's characteristics. Rubinstein provides a comprehensive discussion of the Monte Carlo method.[8] An example of the use of the Monte Carlo method, as applied to an aircraft autoland dispersion analysis, was done by Shakarian.[9] Another example of the use of the Monte Carlo technique is an analysis of a transfer orbit stage guidance system by Bell.[10]

X-43A HXRV Batch Simulation

The SIM is a non-linear six degree-of-freedom (6-DOF) representation of the HXRV. It was developed, and is maintained, by NASA DFRC.[11] The X-43A's entire operation and performance are most accurately simulated by the SIM, which includes models that are necessary to simulate the dynamics of the X-43A vehicle. These models include representations of the actuators, engine, fuel system, vehicle aerodynamics, and many additional subsystems. Representations of the flight software, which include flight systems software, flight controls, guidance, and the PSC, are also coded into the SIM. The flight controls and the PSC were generated using MATLAB® Simulink®, a graphical user interface (GUI) block diagram based software; they are auto-coded to generate the C routines for inclusion into both the operational flight program (OFP) and the SIM. One limitation to the SIM is the lack of ability to model an engine unstart condition. A deliberate decision was made to not attempt to model the unstart phenomenon, as its occurrence is not easily predicted or modeled. This decision is of substantial importance, as noted in the subsequent discussion.

X-43A HXRV Monte Carlo Analysis Tool

A Monte Carlo analysis tool was developed to stress the vehicle system with predicted uncertainties. The X-43A HXRV Monte Carlo Analysis Tool (MCAT) tests the vehicle performance for random and unique sets of input parameter uncertainties. An execution of the MCAT consists of a large number of SIM runs with the first run being nominal and the rest containing different combinations of uncertainties.

Figure 5 is a flowchart graphically representing the stochastic MCAT process. The inputs of each SIM run, such as the uncertainties that will be used, are defined in an input file that is called a SIM input script. The MCAT generates the SIM input scripts and details the number of SIM runs.

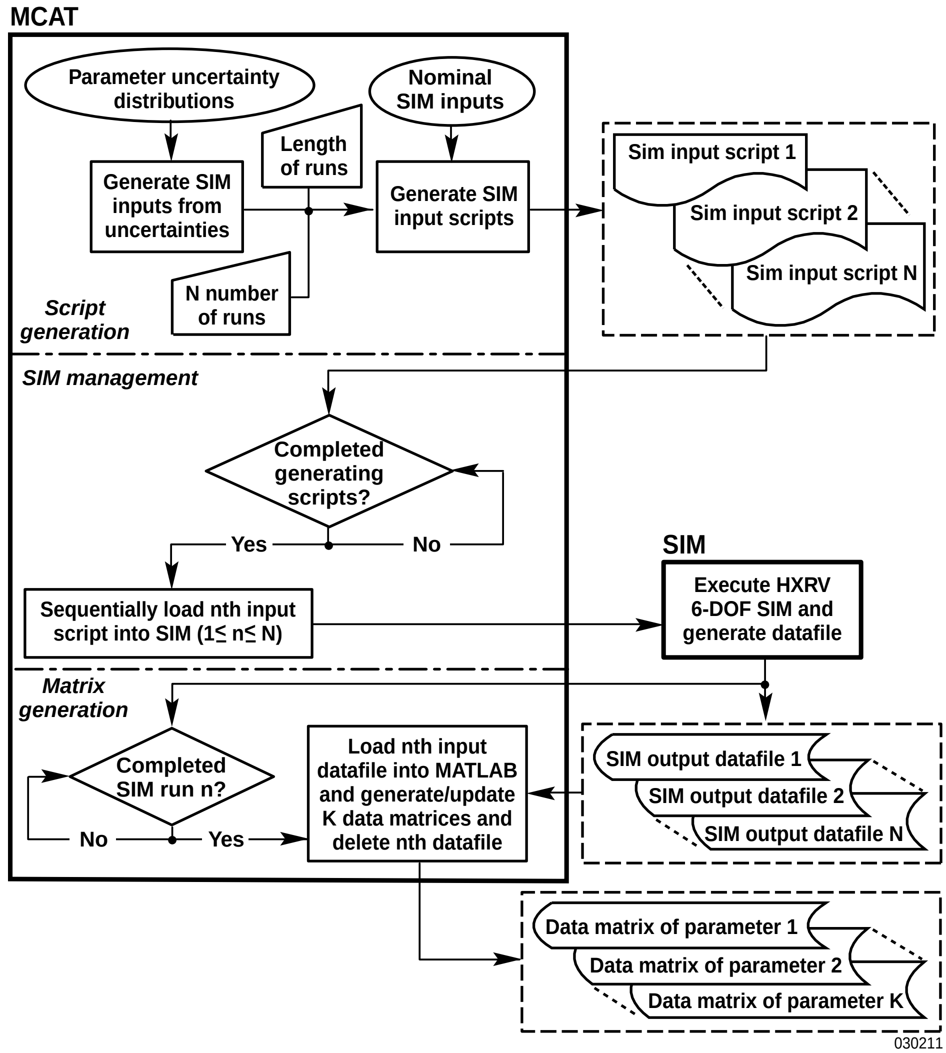


Figure 5. Graphical representation of MCAT process.

The MCAT then uses the SIM input scripts to run the SIM in a batch mode a number of times specified by the MCAT and saves a subset of the SIM parameters, which are recorded for later analysis. The SIM output data of each of these saved parameters are collected from each SIM run into separate matrices (one for each parameter). The data matrices are then stored for future analysis and plotting.

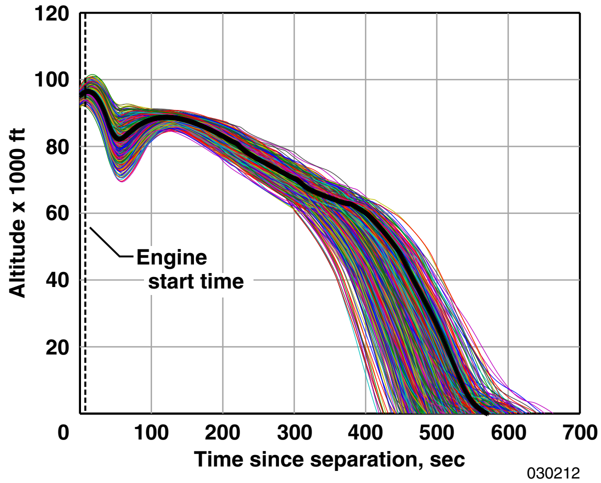
For the MCAT, every input parameter that is varied has an uncertainty expressed in terms of a probability density function. The probability density functions for each input parameter are expressed in terms of its distribution type (uniform or Gaussian), a mean, and a standard deviation (σ). All uncertain SIM input parameters are varied independently. The input parameter values are based upon their particular probability density functions. They are selected within the ± 3 σ bounds for each run with either a uniform or Gaussian distribution (the distributions are specified by the user in the MCAT). If a distribution is Gaussian, the 3 σ bounds encompasses 99.87 percent of the possible values of the uncertain parameter.[12] The uncertainties associated with a parameter were provided by each discipline responsible for that portion of the model (i.e. aerodynamics, propulsion, flight control, etc.). Table 1 shows the number and types of all 158 parameters that are stochastically varied simultaneously in the MCAT.

Table 1. Table of MCAT uncertainties.

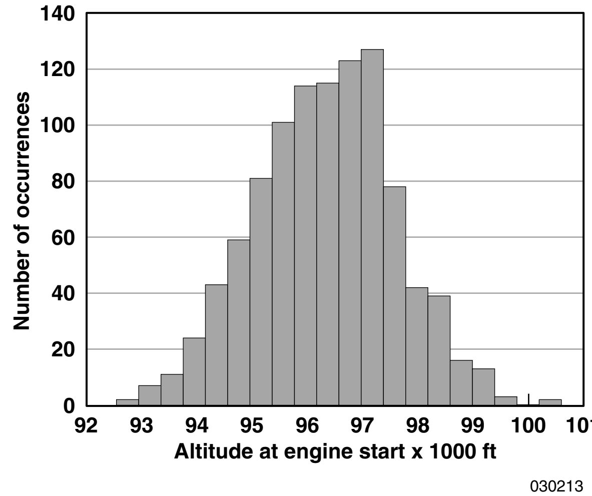
Uncertainty description	# of parameters varied
Separation conditions	12
Mass properties	8
Engine performance	5
Actuator performance	21
Vehicle aerodynamics	17
Flush air data system	8
Winds	48
Atmospheric properties	1
Sensor performance	25
Separation forces and moments	13
Total	158

An example of a SIM uncertainty is the uncertainty of the altitude at which the HXRV separates from the HXLV. During an execution of the MCAT, the value for separation altitude is stochastically selected for each SIM run within a Gaussian distribution between the ± 3 σ values. This uncertainty in separation altitude is applied as an input to the SIM to examine the performance of the HXRV to off-nominal separation conditions and to ensure that there is no significant vehicle performance degradation due to changes in the separation condition.

For this study of the PSC, the analysis focuses on examining the effect input parameter uncertainty has on several output parameters that detail the engine performance. The data matrices were compiled for each parameter of interest and examined graphically by plotting the results from all SIM runs on a single plot. Figure 6(a) shows an example of altitude time histories from the MCAT output data using 1000 SIM runs. Histograms of the data matrices are then used to further analyze and understand the nature of the data. Figure 6(b) shows an example of a histogram of the altitude distribution at the start of the engine experiment (time denoted in fig. 6(a)). These histograms help to quantify the probability functions of each parameter of interest. These probability functions are then examined to evaluate engine performance.



(a) Altitude time histories.



(b) Histogram at engine start time.

Figure 6. Example of altitude time histories and histogram output from MCAT.

A significant input to the MCAT is the number of SIM runs required to obtain convergent solutions. In order to determine the sufficient number of runs for the MCAT to reach a convergent solution, the σ of a series of parameters are examined including maximum angle of attack, maximum acceleration, and maximum Mach number. Figure 7 shows that the σ of such parameters was found to converge after about 1000 runs. Therefore, the common number of SIM runs executed during use of the MCAT is 1000.

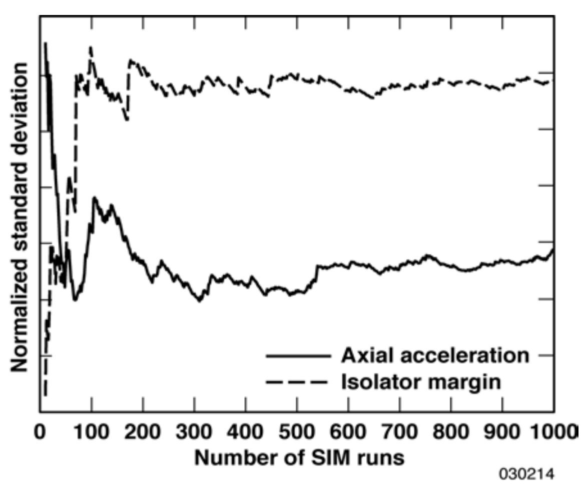


Figure 7. MCAT convergence data.

One limitation to the MCAT is its lack of ability to simulate potential hardware and software failures. It was decided to not attempt to include these types of uncertainties into the MCAT, because the probabilities of these type of failures is not well understood, nor quantified for experimental hardware and software. Therefore, the output data of the MCAT assumes no hardware or software failures.

PROPULSION SYSTEM CONTROLLER ANALYSIS

Output data from the MCAT was used to twice evaluate the performance of the PSC. The first execution was with the unstart protection algorithms disabled (MC1) and the second was with the unstart protection algorithms enabled (MC2). Executing the MCAT with the unstart protection algorithms disabled (MC1) provided a baseline for comparison of the unstart protection algorithms.

Three aspects of the engine performance and operability were selected for evaluation: unstart potential, vehicle acceleration, and duration of successful data. It is a balance between the opposing engine aspects of unstart potential and vehicle acceleration, which embody the balance between risk and goals, respectively. Too much unstart protection adversely affects vehicle acceleration and vice versa. The duration of successful data is an attempt to quantify this balance of risk and goals.

For the first engine performance and operability aspect, unstart potential, a SIM output parameter that relates to isolator margin, was examined. Using this parameter, a value of high isolator margin corresponds to a value of low unstart potential (low risk of unstart), and a low value of isolator margin corresponds to an increased risk of unstart. However, the isolator margin SIM parameter cannot be used to determine if an engine unstart has occurred, as the engine unstart phenomenon is difficult to predict. Similarly, for the second engine performance and operability aspect, a SIM output parameter that measures vehicle acceleration was examined. Of course, high values of vehicle acceleration are considered favorable. For the third engine performance and operability aspect, the duration of successful data, the time during which the HXRV successfully met or exceeded the unclassified acceleration goal (UAG) while maintaining an isolator margin greater than the isolator margin goal (IMG), was examined. The three aspects of the engine performance and operability are discussed below in greater detail.

As MC1 provides a baseline for MC2, the data from MC2 was examined as a risk-reduction/goal-enhancement technique for the HXRV over the MC1 data.

RESULTS AND DISCUSSION

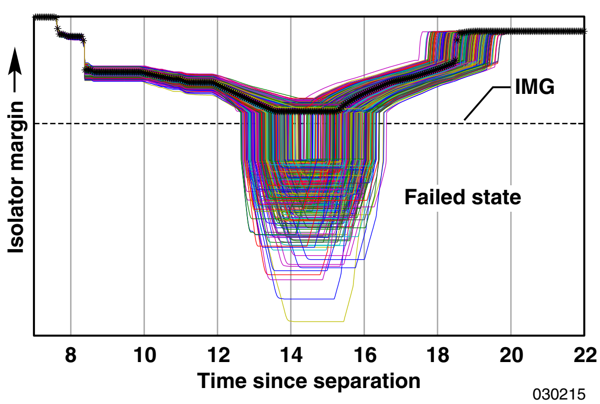
Some of the output data from the Monte Carlo analysis is presented below. Unclassified statistics of the data are presented. A discussion of the statistics is also presented.

Presentation of Monte Carlo Data

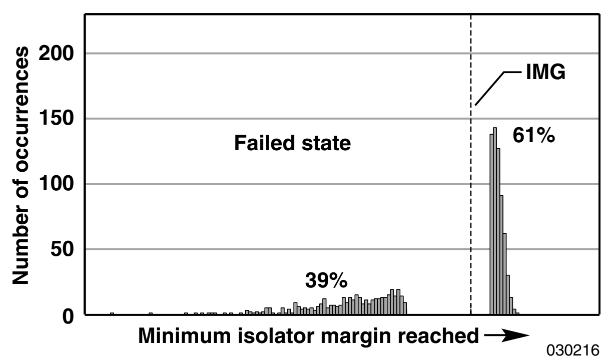
A goal value corresponding to the design point of the engine was selected to evaluate the isolator margin parameter. During any of the 1000 SIM runs per execution of the MCAT, if the value of isolator margin was calculated to reduce below the IMG, the rest of the data from that run was statistically considered to be in a failed state. The approach of using a goal value for isolator margin was taken due to the inability of the SIM to predict the onset of an engine unstart. This approach also provided a quantitative success/failure limit for isolator margin for statistical evaluation.

Figure 8(a) shows the time histories of the isolator margin parameter data for MC1. For some of the traces, the isolator margin drops below the IMG. This shows that some of the SIM runs did exhibit instances in which the isolator margin was calculated to be less than the goal value, or to have been in a failed state. Figure 8(b) is a histogram developed to plot the minimum values of isolator margin that were reached for all of the SIM runs. This was done to evaluate the worst calculated estimate of isolator margin, and, conversely, the highest risk of engine unstart. For MC1, 39 percent of the SIM runs exhibited isolator margin below the goal value, thus 61 percent of the SIM runs were found to be successful with respect to isolator margin.

Figures 9(a) and (b) present the corresponding data for MC2. Very few MC2 cases exhibited isolator margin less than the goal value. Only 3 percent of the SIM runs showed cases where isolator margin decreased below the goal value, thus 97 percent of the runs were found to be successful with respect to isolator margin.

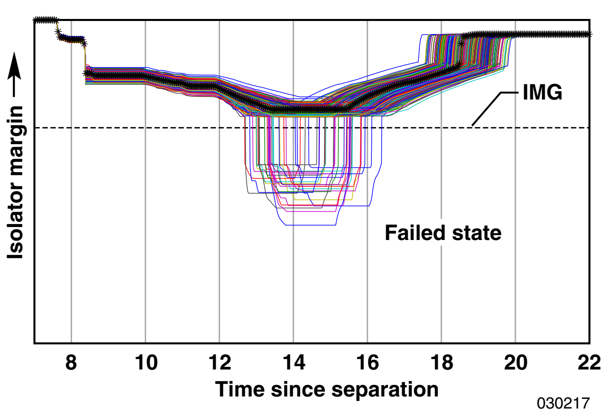


(a) Isolator margin time histories.

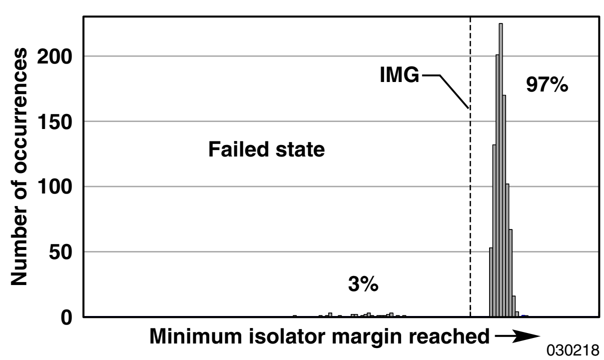


(b) Histogram of minimum isolator margins.

Figure 8. Isolator margin data from MCAT (MC1).



(a) Isolator margin time histories.

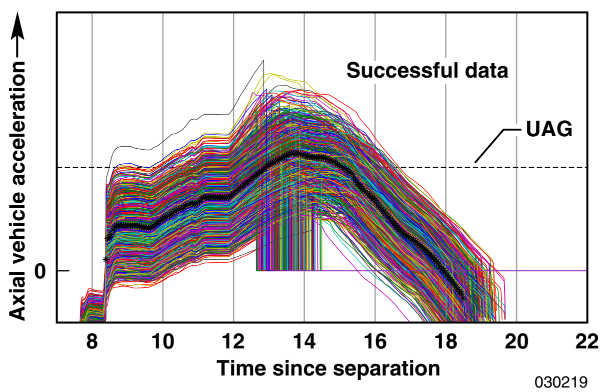


(b) Histogram of minimum isolator margins.

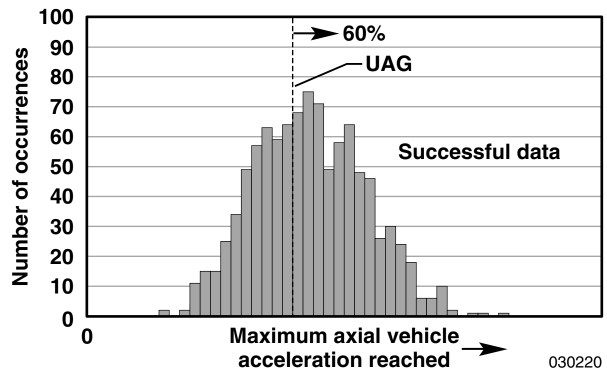
Figure 9. Isolator margin data from MCAT (MC2).

A SIM output parameter of total vehicle acceleration (minus gravity effects) was examined for evaluation of the second engine performance and operability aspect. Figure 10(a) shows the vehicle acceleration data from MC1. For evaluation of this parameter, if during any SIM run the isolator margin value was calculated to have been less than the IMG, the remainder of the acceleration data for that SIM run was considered to be unsuccessful data. For ease of evaluation, the acceleration data that was found to be unsuccessful was set to zero. This can be seen in figure 10(a) where a few of the data traces fall instantaneously to a flat line value of zero. Again, to further evaluate this data, histograms were utilized to examine the probability of maximum acceleration achieved. Figure 10(b) shows the histogram of the maximum acceleration achieved, ignoring any acceleration data that was considered to be in a failed state for the MC1 data. Also shown in this histogram is the UAG. It should be noted here that the UAG is a value greater than zero. For MC1, 60 percent of the SIM runs showed that the acceleration met or exceeded the goal value, or were successful with respect to the UAG.

Figures 11(a) and (b) show the corresponding data for MC2. For MC2, 55 percent of the runs were found to be successful with respect to the UAG.

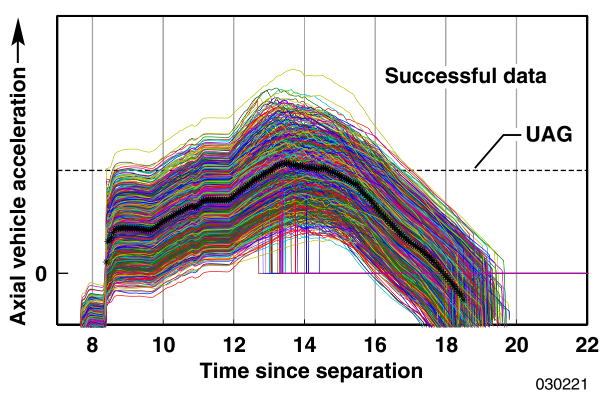


(a) Axial acceleration time histories.

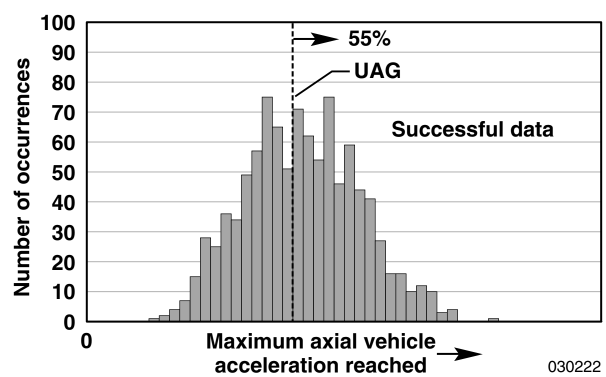


(b) Histogram of maximum axial acceleration.

Figure 10. Axial acceleration data from MCAT (failed state data filtered out) (MC1).



(a) Axial acceleration time histories.



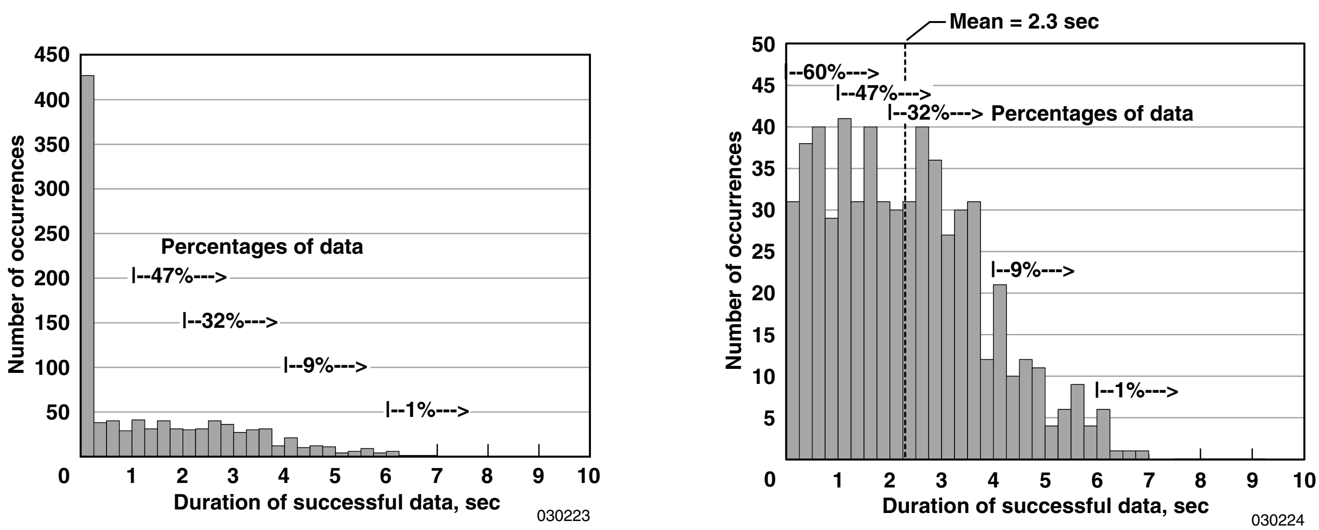
(b) Histogram of maximum axial acceleration.

Figure 11. Axial acceleration data from MCAT (failed state data filtered out) (MC2).

The vehicle acceleration data discussed above and shown in figures 10 and 11 were also used to evaluate the third engine performance and operability aspect: duration of successful data. For each SIM run, the length of time during which the vehicle achieved or exceeded both the IMG and the UAG, was recorded. As before, data that occurred following a reduction of isolator margin below the IMG has been statistically ignored. Data that met these stipulations were considered for this analysis to be successful data. Figure 12(a) shows the histogram of the duration of successful data per SIM run for MC1. The leftmost bar in this histogram shows a substantially larger number of occurrences, because this histogram also includes the instances that did not meet the above-mentioned stipulations. As shown in figure 12(a), 47 percent of SIM runs obtained successful data for at least 1 sec, and 32 percent of the SIM runs obtained successful data for at least 2 sec. The mean of the distribution shown in figure 12(a) is 1.4 sec. Figure 12(b) shows the histogram for MC1 of successful data only. There is no contribution from failed state data. The mean value is 2.3 sec, showing that the average length of successful data is 2.3 sec.

Figures 13(a) and (b) present the corresponding data for MC2. Again, 47 percent of the SIM runs obtained successful data for at least 1 sec, but here 40 percent of the SIM runs obtained successful data for at least 2 sec. The mean of the distribution shown in figure 13(a) is 1.7 sec. Figure 13(b) shows that the average duration of successful data is 3.0 sec.

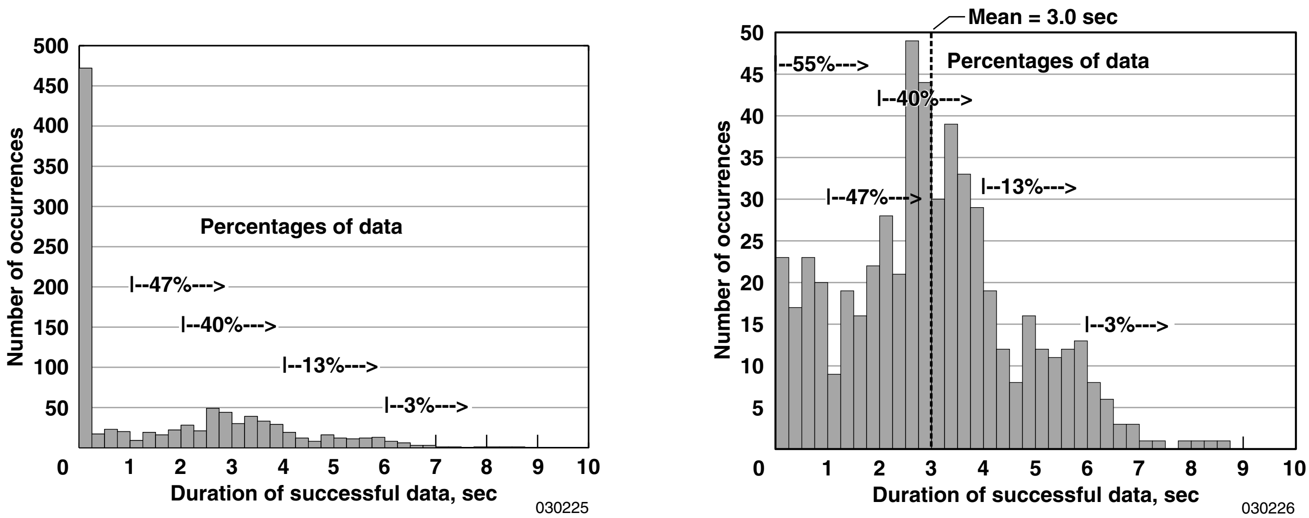
To more clearly present the data in figures 12 and 13, figure 14 shows the percentage of SIM runs that obtained successful data (expressed as probability to obtain successful data) for particular durations of successful data for both MC1 and MC2. This figure shows that although there were more SIM runs obtaining successful data of durations less than 1 second for MC1 (without unstart protection algorithms), the MC2 data shows more SIM runs obtaining successful data of durations greater than 1 sec. The intent of the PSC is to help the HXRV obtain as much successful data as possible, and figure 14 shows that the PSC with unstart protection algorithms provides a higher probability to obtain more successful data.



(a) Includes instances of duration ≥ 0.

(b) Includes instances od duration > 0.

Figure 12. Histograms of duration of successful data (MC1).



(a) Includes instances of duration ≥ 0.

(b) Includes instances od duration > 0.

Figure 13. Histograms of duration of successful data (MC2).

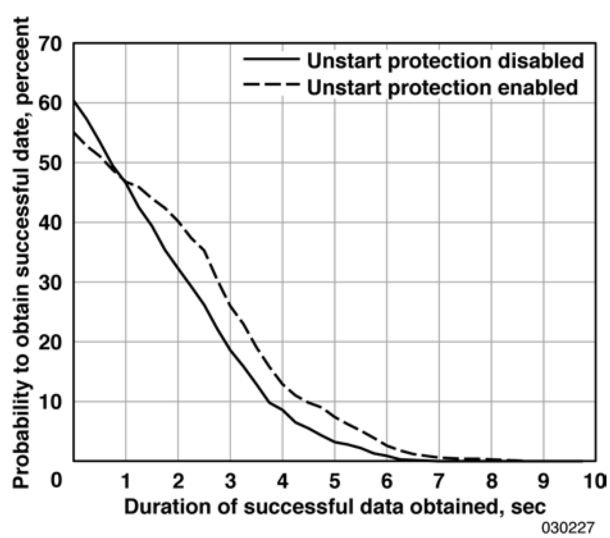


Figure 14. Probability to obtain successful data vs. duration of successful data.

Discussion of Monte Carlo Data

As discussed previously, figures 8 and 9 show that the PSC with unstart protection algorithms is predicted to provide a 36 percent higher probability (97 percent – 61 percent = 36 percent) to achieve the desired isolator margin as opposed to a system without unstart protection algorithms. This shows a significant reduction in unstart potential, as this is the intention of the unstart protection algorithms.

The data from the MCAT also show that 97 percent of the SIM runs show no signs of having an isolator margin value that is less than the IMG. This data suggests that within the limitations of the SIM, there is a very low probability of occurrence for an engine unstart using the PSC unstart protection.

The predicted probability of obtaining successful data, as defined above, is 60 percent with no unstart protection and 55 percent with the PSC unstart protection enabled. This is a small reduction in probability to obtain successful data. However, as mentioned previously, there are limitations to the SIM such as lack of ability to predict engine unstart and lack of modeling of random hardware failures or in-flight anomalies. Thus, 5 percent reduction may not reflect the actual probability of achieving the first-order success criterion of the Hyper-X Program.

Also, the mean value for the duration of successful data, or the length of time during which the vehicle achieved or exceeded both the IMG and the UAG, was 2.3 sec without unstart protection and 3.0 sec with the PSC unstart protection algorithms enabled. This suggests that the PSC unstart protection algorithms provide the HXRV with the ability to obtain a longer duration of successful data.

Figure 14 shows, as a function of duration of successful data, the predicted probability that the X-43A vehicle will meet or exceed the UAG while maintaining an isolator margin greater than the IMG. This suggests that the PSC with unstart protection algorithms provides a greater probability of obtaining more successful data than without these algorithms.

These data suggest a high probability of achieving the first-order success criterion of the X-43 vehicles by utilizing the PSC unstart protection algorithms.

CONCLUDING REMARKS

A Monte Carlo analysis approach was taken to evaluate the performance of the scramjet engine controller for the X-43A. Two Monte Carlo analysis data sets were generated using the developed Monte Carlo Analysis Tool (MCAT). The first analysis data set, used as a baseline for analysis, lacked unstart protection algorithms. The second analysis data set utilized unstart protection algorithms. The Monte Carlo data predict that the Propulsion System Controller (PSC) utilizing unstart protection algorithms reduces the risk of unstart by 36 percent by keeping the engine isolator margin near or above the isolator margin goal (IMG). In fact, the Monte Carlo data predict only a 3 percent chance of occurrence of isolator margin less than the IMG (within the simulation capability of the MCAT). The Monte Carlo data also predict that the PSC utilizing unstart protection algorithms provides adequate control of the engine so as to result in a good probability (55 percent) of achieving or exceeding the unclassified acceleration goal (UAG). Successful data is defined for this paper as data in which the vehicle axial acceleration is greater than the UAG prior to an occurrence of the isolator margin dropping below the IMG. The Monte Carlo data also suggest that through the use of unstart protection algorithms, the predicted duration of successful data the X-43A will generate will be greater than if the PSC contained no unstart protection. The predicted mean value of duration of successful data is 3.0 sec.

Considering all of the above-mentioned data and the limitations of Monte Carlo simulation, the X-43A PSC exhibits high performance and the ability to allow the X-43A vehicle to meet the primary success criterion of the Hyper-X program.

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A Monte Carlo analysis has been conducted to evaluate the performance of the scramjet engine controller for the X-43A. The Propulsion System Controller (PSC) logic was evaluated to assess the effectiveness of a proposed unstart protection algorithm with regard to preventing engine unstarts and achieving vehicle performance goals. The Monte Carlo data obtained from a high fidelity simulation predicts that utilizing the unstart protection logic significantly reduces the risk of unstart by keeping the isolator margin at or above its desired value. The results also show that the unstart protection algorithm does not significantly reduce the probability of meeting the project's primary acceleration goal, thus justifying its suitability for use within the X-43A PSC.

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